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14. ABSTRACT
The principal goal of this project was the attenuation and elimination, through the use of nonlinear energy sinks (NESs), of limit cycle oscillations (LCOs) that occur in aeroelastic systems. The NES is a fully passive device that is able to drastically modify the global dynamics of a system, despite being a local modification. It was demonstrated, through analysis and simulation, that the implementation of the NES on a Van der Pol oscillator, which is well known to exhibit limit cycle behavior, leads to suppression of the LCO over a wide range of the NES parameter space. Examination of the well-known aeroelastic scenario of a cubicaly nonlinear rigid wing in a quasi-steady flow field showed, for the first time, that LCO formation is a consequence of a series of resonance captures and escapes, and that the heave mode response is the unique trigger for the pitch mode LCO. Implementation of the NES on an aeroelastic system revealed that suppression occurs over a broad range of NES parameters in one of three distinct flavors: complete elimination; burst and elimination; and attenuation. All predictions for this configuration were confirmed in a series of wind tunnel tests in the nonlinear aeroelastic test apparatus (NATA) at Texas A&M University. Analysis and simulation indicate an NES with the same total mass distributed among multiple degrees of freedom can be even more effective.

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A New Concept for Flutter Suppression Based on Nonlinear Energy Pumping

Grant Number: FA9550-04-1-0073
Grant Monitor: Dr. Victor Giurgiutiu

Abstract

The principal goal of this project was the attenuation and elimination, through the use of nonlinear energy sinks (NESs), of limit cycle oscillations (LCOs) that occur in aeroelastic systems. The NES is a fully passive device that is able to drastically modify the global dynamics of a system, despite being a local modification. It was demonstrated, through analysis and simulation, that the implementation of the NES on a Van der Pol oscillator, which is well known to exhibit limit cycle behavior, leads to suppression of the LCO over a wide range of the NES parameter space. Examination of the well-known aeroelastic scenario of a cubically nonlinear rigid wing in a quasi-steady flow field showed, for the first time, that LCO formation is a consequence of a series of resonance captures and escapes, and that the heave mode response is the unique trigger for the pitch mode LCO. Implementation of the NES on an aeroelastic system revealed that suppression occurs over a broad range of NES parameters in one of three distinct flavors: complete elimination; burst and elimination; and attenuation. All predictions for this configuration were confirmed in a series of wind tunnel tests in the nonlinear aeroelastic test apparatus (NATA) at Texas A&M University. Analysis and simulation indicate an NES with the same total mass distributed among multiple degrees of freedom can be even more effective.

Objectives

The objectives of this program remained unchanged from those originally proposed. The principal goal of this project was the attenuation and elimination of limit cycle oscillations (LCOs) that occur in aeroelastic systems due to fluid-structure interactions, through the use of nonlinear energy sinks (NESs).

Status of Effort

The concept of LCO suppression through use of a nonlinear energy sink (NES) has now been demonstrated. This was first accomplished for a model problem, the Van der Pol Oscillator. This was followed by examination of a standard aeroelastic model, which led to novel analyses and complete understanding of the triggering mechanism of the LCO. The final step, suppression and elimination of the LCO through the use of the NES, was verified experimentally. Improvements in the form of more efficient utilization of total NES mass, by dividing it among two or more degrees of freedom, with accompanying gains in robustness, have been investigated and show promise. The use of an established aeroelastic analysis program (CAPTSDv), modified to include the NES, is underway in collaboration with AFRL. Work has recently begun on nonlinear system identification and reduced-order modeling tools based on the slow-flow analysis methods applied in the present program.

Accomplishments and New Findings

Research Highlights

This section summarizes key new results of this research program. Much more detail may be found in the related journal papers.

Suppression of LCOs in the van der Pol Oscillator

We studied suppression of the limit cycle oscillations of a van der Pol (VDP) oscillator, utilizing two configurations of non-linear energy sink (NES): grounded and ungrounded. Through computational parameter studies we verified LCO elimination for certain ranges of NES parameters. Then, we established the slow-flow equations to perform numerical and analytical studies of the transient and steady-state dynamics of both configurations. The transient dynamics turned out to involve resonance captures, through which irreversible, passive energy transfer (nonlinear energy pumping or targeted energy transfer) is achieved from the VDP oscillator to the NES. We also performed computational bifurcation analysis by means of numerical continuation to gain some understanding of the dynamics of generation and elimination of energy pumping. The steady-state dynamics showed that the system may possess either subcritical or supercritical LCOs, leading to different degrees of robustness of suppression. These results support the applicability of the NES concept to suppression of instabilities in self-excited systems.

Triggering Mechanisms of LCOs due to Aeroelasticity Instability

We showed that a cascade of resonance captures constitutes the triggering mechanism of limit cycle oscillations (LCOs) due to aeroelastic instability of rigid wings in flow. We considered a two-degree-of-freedom wing model in subsonic flow with cubic nonlinear stiffnesses at the support. Under the assumption of quasi-steady aerodynamics, we applied a complexification/averaging technique to express the dynamics of fluid–structure interactions in terms of three fast-frequency components; these were the two linear natural frequencies corresponding to heave and pitch, and a superharmonic at three times the pitch frequency. Bifurcation analysis of the resulting set of modulation equations governing the slow dynamics was carried out via the method of numerical continuation, and revealed the different types of steady-state motions realized as the parameters vary. It turned out that the LCO triggering mechanism consists of a combination of different dynamic phenomena, taking place in three main stages or regimes: attraction to transient resonance captures, escapes from these captures and, finally, entrapments into permanent resonance captures. We examined numerically and analytically the dynamics at each of these stages, by means of wavelet transform analysis, study of the evolution of appropriately defined phase variables in projections of the phase space of the dynamics, and analysis of instantaneous energy exchanges between the various nonlinear modes involved. The general conclusion is that an initial excitation of the heave mode by the flow acts as the triggering mechanism for the excitation of the pitch mode through nonlinear interactions resulting from the resonance captures and escapes. The eventual excitation of the pitch mode signifies the appearance of an LCO of the wing.

Suppression of Aeroelastic Instability by Means of Broadband, Passive Targeted Energy Transfer, Part I: Theory

Here we investigated passive and nonlinear targeted energy transfers induced by resonant interactions between a single-degree-of-freedom nonlinear energy sink and a 2-DOF rigid wing model. We showed that it is feasible to partially or even completely suppress aeroelastic instability by passively transferring vibration energy from the wing to the NES in an irreversible fashion. Moreover, this instability suppression is achieved by partially or completely eliminating the LCO triggering mechanism. Numerical parametric studies identified three main mechanisms for suppressing aeroelastic instability: recurring burst-out and suppression, intermediate suppression, and complete elimination. We investigated these mechanisms both numerically, using the Hilbert–Huang transform, and analytically, using a complexification-averaging technique. Each suppression mechanism involves strong 1:1 resonance capture during which the NES absorbs and dissipates a significant portion of energy fed from the flow to the wing. Failure of suppression is associated with restoring the underlying triggering mechanism of instability, which is a series of superharmonic resonance captures followed by escapes from resonance. Finally, using a numerical continuation technique, we performed a bifurcation analysis to examine sensitive dependence on initial conditions and thus robustness of instability suppression.

Suppression of Aeroelastic Instability by Means of Broadband, Passive Targeted Energy Transfer, Part II: Experiments

Experimental results corroborating the analysis above were obtained in wind tunnel tests conducted in collaboration with Prof. Thomas Strganac of Texas A&M University, using his nonlinear aeroelastic test apparatus (NATA), and demonstrate that a nonlinear energy sink can improve the stability of an aeroelastic system. The NES was in this case attached to the heave (plunge) degree of freedom of a rigid airfoil which was supported in a low-speed wind tunnel by nonlinear springs separately adjustable in heave and pitch. This airfoil was found to exhibit a limit cycle oscillation at flow speeds above the critical ("flutter") speed of 9.5 m/s, easily triggered by an initial heave displacement. After attachment of a single-degree-of-freedom, essentially nonlinear NES to the wing, the combined system exhibited improved dynamic response as measured by the reduction or elimination of LCO at flow speeds significantly greater than the wing's critical speed. The physics of the interaction of the sink with the wing is examined in detail.

Enhancing Stability of Aeroelastic Instability Suppression Using MDOF NESs

We utilized simultaneous multi-modal broadband targeted energy transfers to multi-degree-of-freedom nonlinear energy sinks (MDOF NESs) to improve robustness of aeroelastic instability suppression of a rigid wing with structural nonlinearities. Numerical bifurcation analysis of limit cycle oscillations (LCOs) of the wing with the MDOF NES attached showed that controlling the lower parameter value for limit point cycle bifurcation so that it occurs above the Hopf bifurcation is crucial to enhancing robustness of LCO suppression. We demonstrated that MDOF NESs can greatly enhance the robustness of LCO suppression, compared to SDOF NESs, with much smaller total mass required in the MDOF case. We also investigated the nonlinear interactions that occur between the aeroelastic modes and the MDOF NES, in an effort to gain a physical understanding of the mechanisms governing instability suppression. We demonstrated that a properly designed MDOF NES provides robustness of aeroelastic instability suppression by efficiently, passively and rapidly transferring a significant portion of unwanted vibration energy to the furthest mass of the NES. Consideration of other types of MDOF NESs suggests that the robustness enhancement is achieved by the concentrated mass effect of the attached NESs.

Significance to the Field

Our ability to completely understand the triggering mechanism underlying LCO formation in aeroelastic systems has led to the development of a completely passive, lightweight, low-cost attachment that, when integrated into the primary system, promotes suppression of potentially damaging limit cycle oscillations.

Relationship to Original Goals

We have found no cause to deviate from our original goals, defined in our proposal.

Relevance to the Air Force's Mission

Presently, the occurrence of LCOs in aircraft structures is a somewhat random problem, due largely to parametric uncertainties and tolerances. This is exacerbated when more complex aeroelastic interactions occur, for example in the wing-store flutter problem. This necessitates considerable analysis and testing, including flight testing of new configurations, by the Air Force; and the result is often a warning to pilots to avoid certain flight regimes. We believe that the NES offers the possibility of eliminating much of this uncertain and dangerous behavior. The addition of a lightweight, low-cost, fully passive, disposable NES to each store is likely to mitigate the wing-store flutter problem entirely. We seek support to demonstrate this capability.

Potential Applications to Air Force and Civilian Technologies

Immediate application of this technology lies in the elimination of the wing-store flutter problem in high-performance aircraft. However, the NES is likely to find application in many systems where LCOs are known to exist; for example in rotating systems with friction.

Personnel

Supported Personnel

- Prof. Lawrence A. Bergman, Principal Investigator
- Prof. Alexander F. Vakakis, Co-Principal Investigator
- Dr. D. Michael McFarland, Co-Principal Investigator
- Dr. Young S. Lee, Graduate Assistant and later Postdoctoral Researcher
- Ms. Melonee M. Wise, Graduate Assistant

Other Personnel

- Dr. Gaetan Kerschen (Fulbright Fellow), University of Liege, Belgium
- Dr. Panagiotis Panagopoulos, National Technical University of Athens, Greece
- Prof. Oleg Gendelman, Technion, Israel

Publications

Archival Journals

- Y. S. Lee, G. Kerschen, A. F. Vakakis, P. Panagopoulos, L. A. Bergman and D. M. McFarland, "Complicated Dynamics of a Linear Oscillator with a Light, Essentially Nonlinear Attachment," *Physica D: Nonlinear Phenomena*, 204(1–2):41–69, May 2005.
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- Y. S. Lee, A. F. Vakakis, L. A. Bergman, D. M. McFarland and G. Kerschen, "Suppression of Aeroelastic Instability by Means of Broadband Passive Targeted Energy Transfers, Part I: Theory," *AIAA Journal*, **45**(3):693–711, 2007.

- G. Kerschen, O. Gendelman, A. F. Vakakis, L. A. Bergman and D. M. McFarland, "Impulsive Periodic and Quasi-periodic Orbits of Coupled Oscillators with Essential Stiffness Nonlinearity," *Communications of Nonlinear Science and Numerical Simulation*, in press.
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- A. F. Vakakis, D. M. McFarland, G. Kerschen, J. Kowtko, and L. A. Bergman, "Nonlinear Energy Pumping: A New Paradigm for Vibration Isolation," 3rd China-Japan-US Symposium on Health Monitoring and Control of Structures, Dalian, China, 13–15 October 2004.
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- Y. S. Lee, G. Kerschen, A. F. Vakakis, P. Panagopoulos, L. A. Bergman and D. M. McFarland, "Surprisingly Complicated Dynamics of a Single-Degree-of-Freedom Linear Oscillator Coupled to a Nonlinear Attachment," 20th ASME Biennial Conference on Mechanical Vibration and Noise, Long Beach, California, 24–28 September 2005.
- Y. S. Lee, A. F. Vakakis, L. A. Bergman, D. M. McFarland and G. Kerschen, "Triggering Mechanisms of Limit Cycle Oscillations in a Two-Degree-of-Freedom Wing Flutter Model," 20th ASME Biennial Conference on Mechanical Vibration and Noise, Long Beach, California, 24–28 September 2005.

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- Y. S. Lee, G. Kerschen, F. Georgiadis, D.M. McFarland, L.A. Bergman and A.F. Vakakis, "An Overview of Targeted Energy Transfer Phenomena in Coupled Oscillators: Theoretical and Experimental Results and System Identification," 11h Conference on Nonlinear Vibrations, Stability, and Dynamics of Structures, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, 13–17 August 2006.

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- D. M. McFarland, P. S. Beran, Y. S. Lee, A .F. Vakakis and L.A. Bergman, "Transonic Aeroelastic Analysis Including the Effects of a Nonlinear Energy Sink," 48th AIAA Structures, Structural Dynamics and Materials Conference, Honolulu, Hawaii, 23–26April 2007. Paper number AIAA 2007–2016.

- Y. S. Lee, A. F. Vakakis, L. A. Bergman, D. M. McFarland and G. Kerschen, "Enhancing Robustness of Instability Suppression by Means of Multi-Degree-of-Freedom Nonlinear Energy Sinks," 48th AIAA Structures, Structural Dynamics and Materials Conference, Honolulu, Hawaii, 23–26April 2007. Paper number AIAA 2007–2205.

- Y. S. Lee, A. F. Vakakis, L. A. Bergman, D. M. McFarland and G. Kerschen, "Passive Suppression of Aeroelastic Instabilities of In Flow Wings by Targeted Energy Transfer to Lightweight Essentially Nonlinear Attachments," submitted to the International Forum on Aeroelasticity and Structural Dynamics, Stockholm, Sweden, 18–20June 2007.

Consultative and Advisory Functions

- L. A. Bergman, D. M. McFarland and A. F. Vakakis, "Nonlinear Energy Pumping: A New Method for Mitigating the Effects of High Energy, Short Duration Transient Loads," presented to the Army Research Office, Research Triangle Park, North Carolina, 9 July 2004.
- A. F. Vakakis, L. A. Bergman, D. M. McFarland, Y. S. Lee, G. Kerschen, P. Panagopoulos and J. J. Kowtko, "Nonlinear Energy Pumping for Vibration Absorption and Aeroelastic Instability Suppression," presented at Sandia National Laboratories, Albuquerque, New Mexico, 13 September 2004.
- Y. S. Lee, D. M. McFarland and L. A. Bergman, "LCO Suppression and Elimination in an Aeroelastic System Using a Nonlinear Energy Sink." Presentation at UIUC to Dr. Clark Allred (Captain, USAF: then Program Monitor), 10 August 2005.

Transitions

- A capability for numerical analysis of realistic aircraft models including effects of nonlinear energy sink(s) has been added to the CAPTSDv computer program to evaluate the NES for use on a structure in transonic flow. Potential applications include mitigation of limit-cycle oscillations (LCOs) and reduction of the limitations they impose on aircraft operations (e.g., on stable speeds and stores configurations). This work was performed at AFRL/VA under the auspices of the AF Summer Faculty Program, 2006.

New Discoveries, Inventions, or Patent Disclosures

- Patent Application, "A Device, a System and a Method for Transferring Vibrational Energy," U.S. Serial No. 10/919,752, filed 17 August 2004.

Honors and Awards

- Prof. Lawrence A. Bergman
  - Fellow, American Society of Mechanical Engineers
  - Associate Fellow, American Institute of Aeronautics and Astronautics